March 22, 1960 W. E. BRADLEY ET AL 2,929,999

SEMICONDUCTIVE DEVICE AND APPARATUS

Filed Sept. 19, 1955 2 Sheets-Sheet 1

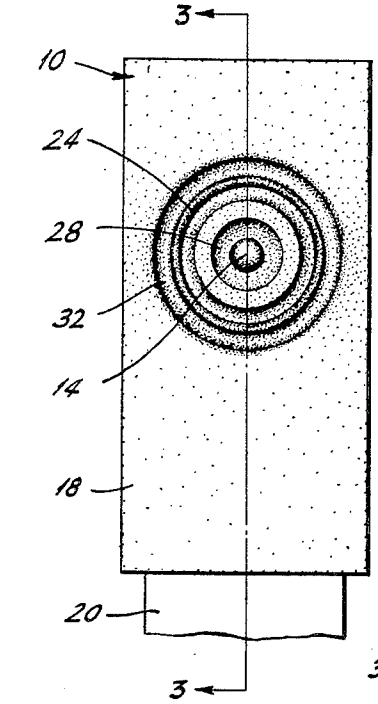


FIG. 1.

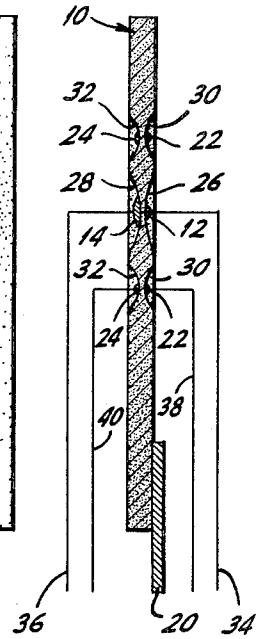


FIG. 3.

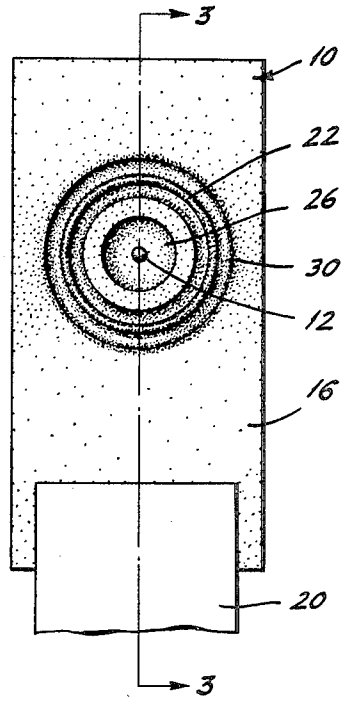


FIG. 2.

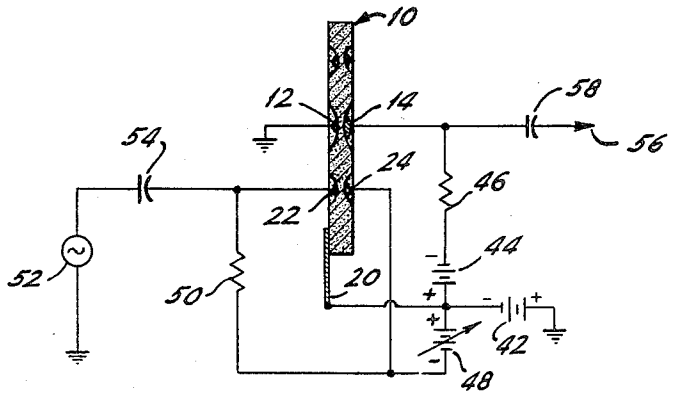


FIG. 4.

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SEMICONDUCTIVE DEVICE AND APPARATUS

Filed Sept. 19, 1955 2 Sheets-Sheet 2

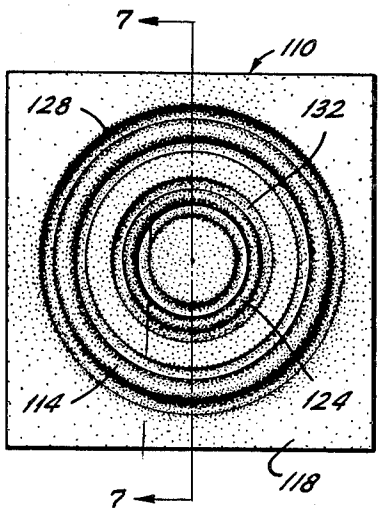


FIG. 5.

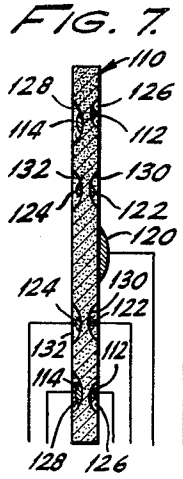


FIG. 7.

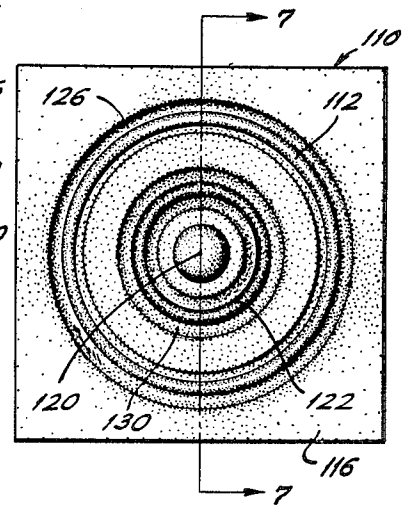


FIG. 6.

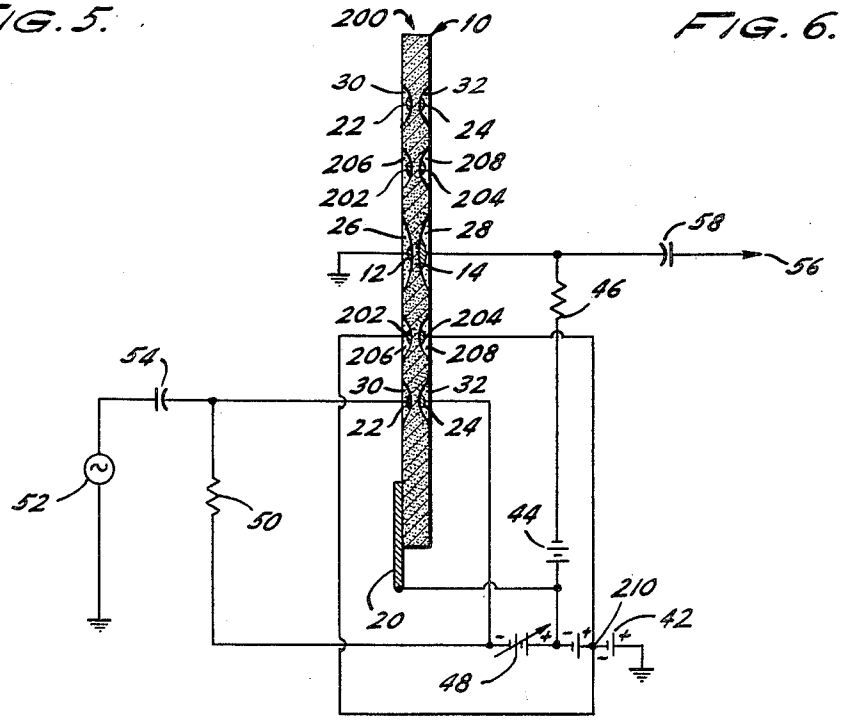


FIG. 8.

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2,929,999

SEMICONDUCTIVE DEVICE AND APPARATUS

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Application September 19, 1955, Serial No. 534,934

3 Claims. (Cl. 330—38)

This invention relates to semiconductive signal-translating devices and to apparatus utilizing such devices. More particularly, it relates to novel semiconductive signal-translating devices having both high input impedance and high gain.

While highly effective for many purposes, semiconductive signal-translating devices which have heretofore been available in the prior art have been limited in their applications by one or more of the often undesirable characteristics of low input impedance or relatively low voltage gain. Either of these characteristics obviously reduces their value for use as voltage amplifiers inasmuch as those devices having a low input impedance will tend to load unduly a voltage source supplying them with an input signal, while those devices having a low gain provide insufficient amplification of the input signal.

To minimize the deleterious effects of the low input impedance which is characteristic of semiconductive devices such as bipolar transistors, it has been necessary heretofore to utilize impedance-transforming devices in the input circuits of these transistors as, for example, step-down transformers coupling the signal source with the input of the transistor. Such transformers are relatively expensive components, in comparison to the resistance-capacitance networks which are commonly used, for example, to couple the signal source to the input grid of a vacuum-tube amplifier stage, and may have undesirable frequency-dependent characteristics tending to limit the bandwidth of the amplifier in which the transformer is included.

However, certain other semiconductive devices are known which possess the high input impedance desired for voltage amplification. One such device is the so-called "analog," or monopolar, transistor, which may typically comprise a body of semiconductive material, to two portions of which are affixed substantially ohmic contacts, and a rectifying electrode system positioned adjacent the current path between the two ohmic contacts. In such analog arrangements, the input impedance seen by a source of input signal voltage coupled to the rectifying electrode system may be relatively high. However, the analog transistor generally has a relatively low gain; moreover, the device is relatively difficult to construct, because it requires two ohmic connections to be made to the semiconductive body. Such connections have been found difficult to fabricate and, as a result, the production costs of the analog transistor have been high when considered in terms of the costs of competing amplifying devices.

It is accordingly an object of the invention to provide a novel semiconductive signal-translating device.

Another object is to provide a semiconductive signal-translating device having both a high input impedance and a high gain.

A still further object is to provide a semiconductive signal-translating device having a high input impedance, but requiring at most only a single ohmic contact.

An additional object is to provide a novel semiconductive signal-translating device which has an excellent high frequency response, and which may have substantial power handling capabilities.

A still further object is to provide a semiconductive signal-translating device which is relatively inexpensive and easy to manufacture.

Yet another object of the invention is to provide a novel semiconductive signal-translating device which is readily adapted for use in summing and modulating arrangements as well as in amplifying arrangements.

In accordance with the invention, these objects are achieved by the provision of a semiconductive signal-translating device which comprises a body of semiconductive material, means for injecting minority-carriers into the body and means for collecting these carriers, a base contact applied to the body, and means, interposed between the base contact and the carrier-injecting means, for varying the electrical resistance between these last two means in response to variations in the value of an applied voltage.

In one preferred emtbodiment of the invention, the minority-carrier injecting and collecting means may respectively have the form of surface-barrier emitter and collector electrodes arranged opposite each other in depressions located on opposing surfaces of the semiconductive body. The means for varying the electrical resistance may comprise a rectifying electrode system arranged to circumscribe the emitter and collector electrodes, while the base contact may be a tab ohmically affixed to the semiconductive body at a position lying outside of the region circumscribed by the rectifying electrode system.

In a second preferred embodiment of the invention particularly suitable for use in transistors having relatively high power-handling capabilities, the base electrode is positioned so that it, instead of the emitter and collector electrodes, is circumscribed by the rectifying electrode system. The emitter and collector electrodes in turn lie in a region of the semiconductive body which is outside of the region circumscribed by the rectifying electrode system. In one arrangement, these electrodes may comprise rings of an appropriate metal, deposited on opposing surfaces of the semiconductive body in a position circumscribing the analog electrode system.

In each of the preferred embodiments of the invention, special provision is made to prevent injected minority-carriers from reaching the resistance-controlling means, thereby to avoid regenerative feedback within the semiconductive structure as well as lowered input impedance. This result is accomplished by utilizing one or more of the following techniques: (1) spacing the minority-carrier injecting means from the resistance-controlling means by substantially more than a minority-carrier diffusion path length; (2) shaping the carrier-collecting means in a manner such that it tends to trap minority-carriers drifting toward the resistance-controlling means; or (3) interposing rectifying guard electrodes between the carrier-injecting means and the resistance-varying means.

In the operation of the foregoing devices, the minority-carrier injecting means is biased, with respect to the base contact, in the polarity of easy conduction, thereby to inject minority-carriers into the semiconductive body. The minority-carrier collecting means is biased in that polarity, with respect to the emitting means, which tends to attract the injected minority-carrier. The resistance-varying means is biased, with respect to the base contact, in the polarity of difficult conduction, whereby this means tends to deplete of current carriers the region of the semiconductive body adjacent to it, and hence to raise the electrical resistance of the current path between the base contact and the minority-carrier injecting means. A

voltage-varying signal applied to the resistance-varying means therefore produces corresponding variations in the resistance of the current path between the base contact and the injecting means, and hence, in the amount of base current flowing into the region of the carrier-injecting means. These variations in base current, in turn, vary the potential of the semiconductive body in the vicinity of the injecting means and hence vary the number of minority-carriers injected thereby. A a result, the number of minority-carriers collected by the collecting means is also varied in acordance with the voltage-varying signal. These last-named variations may be utilized to produce voltage variations by including a suitable load device in circuit with the injecting and collecting means.

It will be appreciated that the structure, as operated above, exhibits a very high input impedance by reason of the fact that the voltage-varying input signal is applied to a reverse-biased rectifying electrode. In addition, the voltage gain of the device is relatively great, inasmuch as the input signal in effect undergoes amplification of two types, first, that produced by the portion of the structure comprising the base contact, the resistance-varying means and the minority-carrier injecting means, and second, that produced by the minority-carrier injecting means, the minority-carrier collecting means and the adjacent base region. Moreover, these desirable results are accomplished in a single semiconductive structure which, because it needs at most only one ohmic contact, is relatively simple to construct and lends itself to mass-production techniques.

Other advantages and features of the invention will become apparent from a consideration of the following detailed description, taken in connection with the accompanying drawings, in which:

Figures 1 and 2 are plan views showing the two opposite electrode-bearing surfaces of a device constructed in accordance with the invention;

Figure 3 is a cross-sectional view of the structure shown in Figures 1 and 2;

Figure 4 is a schematic diagram of signal-translating apparatus utilizing the semiconductive structure shown in Figures 1 to 3;

Figures 5 and 6 are plan views showing the two electrode-bearing surfaces of a second embodiment of our novel semiconductive structure;

Figure 7 is a cross-sectional view of the semiconductive structure shown in Figures 5 and 6; and

Figure 8 illustrates a third embodiment of our novel semiconductive structure, arranged in signal translating apparatus.

Referring now to Figures 1, 2 and 3, there is shown diagrammatically one of the preferred forms of our novel semiconductive structure, which we shall hereinafter refer to as the compound transistor. The embodiment of the compound transistor shown in Figures 1 to 3 comprises generally a body of semiconductive material in the form of a thin rectangular wafer **10** of N-type germanium; minority-carrier injecting and collecting means which in this embodiment comprise, respectively, surface-barrier emitter and collector contacts **12** and **14**, arranged coaxially on opposing surfaces **16** and **18** respectively of body **10**; body contacting means which, in the embodiment, comprise a base tab **20** affixed to surface **16**, at one end of body **10**, in a substantially ohmic manner; and voltage-responsive resistance-varying means interposed between the contacting and injecting means, which resistance-varying means comprise, in this embodiment, a pair of annular surface-barrier electrodes **22** and **24**, respectively, which are arranged opposite one another on surfaces **16** and **18**, respectively, and which are coaxial with and circumscribe emitter and collector electrodes **12** and **14**, respectively.

In order to promote efficient collection by collector **14** of minority-carriers injected by emitter **12**, close spacing of these electrodes is provided by depositing them within

substantially coaxial depressions **26** and **28**, respectively, which are provided on opposing surfaces **16** and **18** respectively of body **10**. To the same end of efficient minority-carrier collection, collector **14** preferably has a diameter substantially longer than that of emitter **12**, for example, approximately twice as long.

Moreover, to avoid undesirable regeneratively feedback and lowered input impedance, which may be brought about by the transfer to resistance-varying electrodes **22** and **24** of minority-carriers injected by emitter **12**, it is a feature of the invention in its preferred form that electrodes **22** and **24** are spaced from emitter **12** by a radial distance substantially greater than the minority-carrier diffusion length which is characteristic of the semiconductive material of which body **10** is composed. Additionally, to provide a substantial amount of control over the resistance of the current path between base tab **20** and emitter **12**, resistance-varying electrodes **22** and **24** preferably are separated from one another by a distance less than twice the thickness of the current-carrier depletion zone which is produced when a reverse-biasing potential applied to either electrode **22** or **24** has a value equal to that critical reverse-biasing voltage E_{max} at which avalanche breakdown begins within the semiconductive body **10**. To achieve this reltaively close spacing between electrodes **22** and **24**, annular, coaxial, and equidiameter depressions **30** and **32** are provided on body surfaces **16** and **18** respectively, within which depressions are deposited rectifying electrodes **22** and **24** respectively.

Connections to the various electrodes are made by attaching lead wires thereto in a substantially ohmic manner. Thus, in the embodiment shown, lead wires **34**, **36**, **38** and **40** are affixed ohmically to electrodes **12**, **14**, **22** and **24**, respectively, of the compound transistor.

In a typical arrangement, semiconductive body **10** is constituted of N-type monocrystalline germanium having a bulk resistivity of between 2 and 5 ohm-centimeters and a bulk hole lifetime of about 200 microseconds. As aforementioned, body **10** may have the form of a substantially rectangular wafer, which wafer typically may be about 0.100 inch long, 0.050 inch wide, and 0.003 inch thick. The depressions **26** and **28** each may have a surface diameter of about 0.012 inch and a depth of about 0.0014 inch, i.e. a depth such that about 0.0002 inch of germanium separates depressions **26** and **28** at their point of closest approach. Depressions **30** and **32** may each have a mean diameter of 0.025 inch and a width of about 0.010 inch; their depth may be about 0.0013 inch each, i.e. a depth such that 0.0004 inch of germanium separates depressions **30** and **32** at their point of closest approach.

The emitter electrode **12** may have a diameter of 0.004 to 0.006 inch, while collector electrode **14**, which preferably has a diameter substantially greater than that of emitter **12**, may have a diameter of 0.006 to 0.008 inch. Lastly, rectifying electrodes **22** and **24** may each have a mean diameter of 0.025 inch and a width of 0.005 inch.

Surface barrier electrodes **12**, **14**, **22** and **24** may each be formed by depositing a suitable metal, such as indium or zinc, within the appropriate depression, by a process referred to hereinafter. Base tab **20**, and lead wires **34**, **36**, **38** and **40** may each be composed of nickel, and may be respectively attached to surface **16**, and to their respective electrodes, by means of a tin solder.

Figure 4 illustrates a simple amplifying stage constructed in accordance with our invention, wherein the gain-providing element comprises the compound transistor shown in Figures 1 to 3, and corresponding parts are indicated by corresponding numerals. In this circuit, it is assumed that the semiconductive body **10** of the compound transistor is of N-type germanium. Accordingly, in order to produce minority-carrier injection by emitter electrode **12**, that electrode is established at a potential positive with respect to base tab **20**, while, in order to effect minority-carrier collection, collector **14** is established at a potential negative with respect to emitter **12**

and preferably negative with respect to base tab **20**. In the specific arrangement illustrated in Figure 4, these potentials are established by connecting base tab **20** of the compound transistor to the negative pole of a source of direct voltage **42** whose positive pole is connected to a point at ground potential, while connecting emitter **12** directly to the point at ground potential. In addition, collector **14** is supplied with a potential which is negative with respect to the potentials both of emitter **12** and of base tab **20** by means of a source of direct voltage **44** having its positive pole connected to base tab **20**, and having its negative pole connected to collector **14** by an output load device represented by resistor **46**.

In accordance with the invention in one aspect, the rectifying electrodes **22** and **24** are reverse-biased with respect to the base of the compound transistor by means of a potential negative with respect to that of base tab **20**. This negative potential is supplied by a source of direct voltage **48** which has its positive pole directly connected to the base tab **20** and its negative pole directly connected to rectifying electrode **24**. Electrode **22** is also connected to the negative pole of source **48**, via an input impedance represented by a resistor **50**. To permit a critical adjustment of the potential difference between base tab **20** and electrodes **22** and **24** respectively, source **48** is preferably one whose output voltage can be adjusted.

Because each of the rectifying electrodes **22** and **24** is reverse-biased with respect to base tab **20**, each acts, in a manner well known to the art, to produce a current-carrier depletion zone, within the constricted region of body **10** lying between them, whose extent is directly dependent upon the value of the reverse-biasing potential-difference between base tab **20** and electrodes **22** and **24**. Accordingly, as the value of this reverse-biasing potential difference is increased from zero, the electrical resistance between base tab **20** and the region of body **10** adjacent emitter electrode **12** and collector electrode **14** increases, in substantially direct dependence thereupon. At a critical value of this potential difference, which value is inversely dependent upon the bulk resistivity of the semiconductive material of which body **10** is fabricated, and is directly dependent upon the thickness of body **10**, substantially all of the current carriers present between electrodes **22** and **24** are extracted. As a result, the resistivity of body **10** becomes extremely high in this region, and the resistance of body **10** between base tab **20** and the region of body **10** between electroeds **22** and **24** becomes correspondingly high.

To obtain the largest amount of variation in resistance between base tab **20** and the aforementioned region of body **10**, in response to a variation in the value of an applied signal, it is necessary that the spacing be small between the depletion zones produced by potentials applied to electrodes **22** and **24** respectively. However, if the thickness of body **10** between these electrodes is too large, the desired small spacing between the depletion zones cannot be produced for voltages less than that for which harmful avalanche breakdown occurs within the semiconductive body. Accordingly, it is highly desirable that this body thickness be as small as possible, consistent with the requirements of mechanical strength, and, in any event, be less than twice the depletion zone thickness at which avalanche breakdown begins.

In the specific arrangement shown in Figure 4, rectifying electrode **24** is maintained at a fixed back-biasing potential as determined by the output voltage of source **48**, while the value of the back-biasing potential applied to rectifying electrode **22** is varied in accordance with variations in a time-varying input signal voltage supplied by a source **52** which is coupled to electrode **22** by a blocking capacitor **54**. The value of the reverse-biasing potential supplied by source **48** is adjusted to be one intermediate zero and the aforementioned critical potential which cuts off current through the annular constriction in body **10**. In addition, the maximum variation in amplitude of the input signal supplied by source **52** may be chosen in a manner such that electrode **22** is never driven to a zero or positive potential with respect to base tab **20**, nor to a potential so negative that current flow through the aforesaid annular constriction of body **10** is cut off.

Under these conditions, the electrical resistance across this annular constriction is varied in a manner directly dependent upon the variations in amplitude of the input signal supplied by source **52**. When the signal at electrode **22** becomes more positive, the electrical resistance across the construction falls. As a result, an increased base current flows between base tab **20** and emitter **12**, and the potential of body **10** adjacent emitter **12** becomes more negative in response to the negative potential supplied to tab **20**. Since emitter **12** is maintained at ground potential, this negative swing in the potential of body **10** adjacent emitter **12** causes emitter **12** to inject into body **10** an increased number of minority-carriers. This increased number of minority-carriers injected by emitter **12** in turn results in a directly proportional increase in the number of minority-carriers collected by collector **14**, i.e. a directly proportional increase in the minority-carrier current flowing through load resistor **46**. In short, it is seen that a positive-going variation in signal voltage applied to electrode **22** produces a positive-going increase in the potential at collector **14**. This collector-voltage variation may then be supplied to an output terminal **56**, which is coupled to collector **14** by a blocking capacitor **58**.

With regard to the just-described mode of operation of our semiconductive structure as utilized in the amplifying arrangement of Figure 4, it will first be noted that the input impedance seen by source **52** looking into electrode **22** is very high, e.g. of the order of 50,000 to 100,000 ohms, because rectifying electrodes **22** and **24** are operated in their reverse-biased conditions. Moreover, it will be appreciated that the amplifier has a high voltage gain, which may be of the order of 40 to 60 decibels. This high gain is achieved for two reasons: first, only a relatively few current-carriers are present in the constricted annular region of body **10**, between electrodes **22** and **24**. As a result, a relatively small change in voltage at electrode **22** produces a relatively large change in the number of current carriers in the annular constriction, and a correspondingly large change in the emitter-to-base current, all of which must flow through the constriction. This large change in emitter-to-base current produces, in turn, a large change in the potential of body **10** adjacent emitter **12**. Consequently, a large change takes place in the number of minority-carriers emitted by emitter **12**. Substantially all of the minority-carriers emitted by emitter **12** are collected by collector **14**, by reason of the extreme closeness of these two electrodes and the fact that the diameter of collector **14** is larger than that of emitter **12**. Accordingly, this large change in minority-carrier emission is substantially completely reflected in a corresponding change in the collector current flowing through output load **46**. Since the impedance of this load may be relatively high, the voltage variation produced thereacross, in response to the voltage variation applied to electrode **22**, is a highly amplified replica of the latter variation.

In our novel arrangement of Figure 4, the circuit components may typically have the following values:

Source 42	volts D.-C.	3
Source 44	do	3
Resistor 46	ohms	10,000
Source 48	volts D.-C.	5 to 15
Resistor 50	ohms	50,000
Capacitor 54	microfarads	0.5
Capacitor 58	do	0.1

It is to be understood that these values are exemplary only and that we do not intend that the scope of our invention shall be limited thereto.

Moreover, it is, of course, to be understood that the arrangement of Figure 4 represents only one of the many circuit arrangements in which out compound transistors may usefully be employed. For example, the arrangement of Figure 4 may readily be converted into an adding circuit merely by inserting an input impedance (not shown) in series with the connection between rectifying electrode **24** and the negative pole of source **48**, and by coupling to electrode **24** the source (not shown) of the signal to be added to that of source **52**. The value of the signal produced at output terminal **56** is then substantially proportional to the sum of the values of the input signals supplied to electrodes **22** and **24**.

In addition, the compound transistor is readily adapted for use as a modulating element by supplying one of the input waves (either the carrier wave or the intelligence wave) to rectifying electrode **22** while supplying the other wave to emitter electrode **12**. There will then be produced, at output terminal **56**, a wave whose amplitude is proportional to that of the carrier-wave, amplitude-modulated in accordance with the intelligence wave.

With the foregoing discussion in mind, it will be clear to those skilled in the art that our compound transistor may be utilized in numerous other circuit arrangements. For example, by appropriate adjustment of the bias applied by source **48** to electrodes **22** and **24**, and of the maximum applitude excursion of a sinusoidal signal signal supplied by source **52**, a pulsatile waveform may be generated at output terminal **56**. In this regard, it is noted that, in a compound transistor having the exemplary dimensions given hereinbefore, the transistor has a substantial output at collector **14** in response to input signals at electrode **22** having frequencies up to (and beyond) 30 mc./sec.

Moreover, in those instances in which phase-inverter operation is desired, it is only necessary to insert an appropriate load impedance in series with the connection between the emitter **12** and the point at ground potential, to produce, at emitter **12**, an output signal in phase opposition to that produced at collector **14**.

The fabrication of the embodiment of our compound transistor which is shown in Figures 1 to 3 may be accomplished with relative ease by utilizing the jet electrolytic process described in copending patent application Serial No. 472,824 of J. W. Tiley and R. A. Williams, filed December 3, 1954, entitled "Semiconductive Devices and Methods for the Fabrication Thereof," and assigned to the assignee of the present application. As an example, depressions **26** and **28** may be excavated from body **10** by directing against body **10** a fine jet of electrolyte of appropriate diameter whose electrical potential is negative with respect to body **10**. Preferably this electrolyte contains ions of the metal eventually to be deposited in the excavated depression as a surface barrier electrode. After the depression has been excavated to the desired depth, an area electrode of the surface-barrier type may be deposited therein by reversing the polarity of the potential at which the electrolyte is maintained. The properties of the surface-barrier electrodes thus formed and suitable for emitter and collector are discussed in detail in copending patent application Serial No. 472,826 of R. A. Williams and J. W. Tiley, filed December 3, 1954, entitled "Electrical Device," and assigned to the assignee of the present application.

Annular depressions **30** and **32** may also be excavated, and annular rectifying electrodes **22** and **24** deposited by the jet electrolytic process described in the aforementioned application Serial No. 472,824. As pointed out in that application, excavation may be accomplished by rotating the body about an axis passing through the midpoints of depressions **26** and **28**, while simultaneously impinging body **10** with an etching jet whose center of impingement is displaced from the aforesaid axis by the mean radius of the annular excavation. Deposition of electrodes **22** and **24** may again be accomplished by utilizing an electrolyte containing ions of the metal to be plated, and applying to the electrolyte a potential poled positive with respect to the body.

In each of the foregoing operations, the depth to which the excavation has proceeded at any time may be determined and controlled by any of a variety of techniques, including the punch-through technique described in the aforementioned application Serial No. 472,824, the bias-controlled etching technique described in copending patent application Serial No. 418,887 of W. E. Bradley, filed March 26, 1954, and entitled "Electrical Method and Device," the infra-red spectral measurement technique described in copending patent application Serial No. 449,347 of R. N. Noyce, filed August 12, 1954, and entitled "Electrical Method and Apparatus," and the colorimetric technique described in patent application Serial No 424,704 of T. V. Sikina, filed April 21, 1954, and entitled "Method and Apparatus for Producing Semiconductive Structures." Each of these applications is also assigned to the assignee of the present application.

A second preferred embodiment of our novel compound transistor which is particularly useful in power transistor applications is shown at Figures 5, 6 and 7 of the drawings. The latter arrangement, while comprising electrodes having the same functions as the electrodes embodied in the structure illustrated in Figures 1 to 3, differs from this structure in that the electrodes are arranged in an order inverse to that of Figures 1 to 3. Thus, in the arrangement of Figures 5 to 7, a base electrode **120**, corresponding to base tab **20** of the preceding embodiment, is positioned centrally upon a semiconductive body **110** of N-type monocrystalline germanium, which may have substantially square major surfaces **116** and **118** respectively. The base electrode **120** preferably makes a substantially ohmic contact with body **110** and may be fabricated in various well-known manners, e.g. by sandblasting, on surface **116**, an area whose shape is determined by the aperture of a mask applied to this surface, and by vaporizing onto this sandblasted area a layer of pure tin or other metal which has the property of bonding substantially ohmically to germanium.

An annular excavation **130**, coaxial with electrode **120**, is formed on surface **116** of body **110** while, on the opposite surface **118** excavation **132** is formed coaxial and codiametral with excavation **130**. These excavations correspond to excavations **30** and **32**, respectively of the preceding embodiment. Within depressions **130** and **132** are located rectifying electrodes **122** and **124**, respectively. These electrodes, which may be surface-barrier electrodes deposited by the aforementioned jet electrolytic process, correspond to electrodes **22** and **24**, respectively, of the preceding embodiment. As in the preceding embodiment, the thickness of germanium separating electrodes **122** and **124** is preferably established at a value less than twice the depth of the current-carrier depletion region which is produced when a reverse-biasing potential, applied to either electrode **122** or **124**, has a value equal to the critical reverse-biasing voltage E_{max} at which avalanche breakdown begins within body **110**.

The compound transistor of this second preferred embodiment additionally comprises an annular emitter electrode **112** and an annular collector electrode **114**, which electrodes are arranged, within annular excavations **126** and **128** respectively, substantially coaxially with the other electrodes of the transistor. Excavation **126** is formed on surface **116** while excavation **128** is formed on surface **118**. Emitter electrode **112** and collector electrode **114** may each be a surface-barrier electrode formed by using the aforementioned jet electrolytic process.

The mean diameters of annular excavations **126** and **128** are such that the separations of emitter and collector electrodes **112** and **114** from rectifying electrodes **122** and **124**, respectively, are considerably greater than the diffu-

sion length of minority-carriers within body **110**. The reason for this is to avoid a substantial flow of minority-carriers from the emitter to an input electrode, e.g. either electrode **122** or electrode **124** of the transistor. As discussed hereinbefore, such a flow of minority-carriers produces a lowered input impedance, as well as undesirable regenerative feedback tending to produce unstable operation of the transistor.

It will be noted, however, that the mean diameter of depression **128**, containing collector electrode **114**, is slightly smaller than the mean diameter of depression **126**, containing emitter electrode **112**. Moreover, the width of emitter electrode **112** is substantially smaller than the width of collector electrode **114**. As a result, the inner boundary of annular collector electrode **114** is substantially closer to the axis of the electrodes than is the inner boundary of annular emitter contact **112**. This collector construction serves to trap more efficiently those minority-carriers emitted by emitter **112** which are diffusing toward rectifying contacts **122** and **124**. Thus, this emitter-collector geometry militates against regenerative feedback of minority-carriers to electrodes **122**, **124**, and also increases the percentage of minority-carriers transferred from the emitter **112** to the collector **114** of the compound transistor.

The mode of operation of this embodiment of our compound transistor is substantially the same as that of the first embodiment shown in Figures 1 to 3. Accordingly, the semiconductive structure of Figures 5 to 7 may be biased and operated in the manner described in connection with Figure 4, due regard being had to the interchanged positions of the emitter-collector contacts and the base contact. However, the compound transistor of Figures 5 to 7 is capable of providing amplification at substantially higher power levels than the transistor of Figures 1 to 3, by reason of the substantially larger areas of the annular emitter and collector electrodes **112** and **114**, respectively. Consequently, the embodiment of Figures 5 to 7 finds particular application in power amplifiers such as audio power amplifiers.

Still another arrangement according to our invention is shown in Figure 8. This arrangement embodies a compound transistor having generally the structure of the transistor shown in Figures 1 to 3, but comprising an additional pair of rectifying electrodes **202** and **204**. These electrodes are positioned on body **10** intermediate the emitter and collector electrode assembly **12**, **14** and the rectifying electrode assembly **22**, **24** at a distance from the emitter and collector which is preferably substantially greater than the aforementioned minority-carrier diffusion length. In the arrangement shown, electrodes **202** and **204** may be deposited within annular depressions **206** and **208**, respectively, which may be positioned on the opposing surfaces of body **10** substantially coaxially with depressions **26**, **28**, **30** and **32**. These depressions **206** and **208** may be excavated by utilizing the aforementioned jet electrolytic process, and rectifying electrodes **202** and **204**, which may be surface-barrier electrodes, may be deposited by the same process.

Rectifying electrodes **202** and **204** are utilized to collect any stray minority-carriers injected into body **10** by emitter **12** which may have diffused into the vicinity of electrodes **202** and **204**. The purpose of collecting these minority-carriers in this manner is to reduce even further the possibility that minority-carriers from the emitter may reach the input electrodes, particularly input electrode **22**, and thereby produce the aforementioned undesirable feedback effect as well as lowered input impedance. To this end, compound transistor **200** may be connected in the arrangement of Figure 8, which is similar to that of Figure 4, but in which electrodes **202** and **204** are supplied with a small reverse-biasing potential. This potential is sufficient to cause electrodes **202** and **204** to collect those minority-carriers which diffuse into their vicinity, but is insufficient to increase substantially the resistance of body **10** within the annular constriction thereof lying between electrodes **202** and **204**. This reverse-biasing potential may be derived, for example, from a tap **210** on source **42**, which tap supplies a voltage whose value is less than that supplied to collector **14**, to the end that electrodes **202** and **204** shall not compete with collector **14** for minority-carriers. Inasmuch as the circuit arrangement of Figure 8 has substantially the same mode of operation as that of the arrangement of Figure 4, it is believed unnecessary to discuss this arrangement in greater detail.

The two principal embodiments of our novel compound transistor described in detail hereinbefore represent only certain preferred structures chosen from among the numerous arrangements falling within the scope of our invention. Thus, while, in each of the aforedescribed embodiments of our compound transistor, two rectifying input electrodes are provided, (i.e. electrodes **22** and **24** in the embodiments of Figures 1 to 4, and 8, and electrodes **122** and **124** in the embodiment of Figures 5 to 7), only a single rectifying electrode to which the input signal is supplied is in fact essential. However, when the second rectifying electrode is omitted, it is usually desirable to cleanse carefully the surface area to which this electrode is normally affixed and to coat this area with an inert material, such as an epoxy resin plastic. This coating then protects the surface from contaminants which might produce high-conductivity channels therealong. Moreover, the maximum thickness of the body underlying the single rectifying electrode is ordinarily only half of the maximum thickness which is permissible when two rectifying electrodes are used, thereby to provide effective control over the base-to-emitter resistance.

In addition, the various rectifying contacts indicated in the several embodiments need not be surface-barrier area contacts but, depending on their functions, may take any one of a variety of forms. More particularly, such contacts may alternatively be P–N junction contacts.

Moreover, compound transistors according to our invention may have electrode arrangements whose geometry differs substantially from those described hereinbefore. Thus, in the arrangements wherein the relative position of the electrodes are those shown in Figures 1 to 3, it is not necessary that rectifying electrodes **22** and **24** be annular in geometry, so long as these electrodes are positioned so as to be able to exert substantial control over the base-to-emitter current. These electrodes, for example, may alternatively have the geometry of linear bars located opposite one another on opposing surfaces of body **10** and extending across body **10** at an orientation such as to divide body **10** into two portions, one containing base tab **20** and the other containing emitter and collector electrodes **12** and **14** respectively.

In addition, emitter and collector electrodes **12** and **14** need not be located on opposing surfaces of body **10**, but may be positioned on the same surface thereof. In one such arrangement, for example, there may be arranged on one surface of the semiconductive body a centrally-positioned emitter electrode, a collector electrode of annular form and concentric with the emitter electrode, a rectifying input electrode, also annular in form, which has a diameter greater than that of the collector electrode and is concentric therewith, and a base contact affixed to the body outside of the region surrounded by the input electrode. In still another alternative arrangement, the emitter and collector electrode may both be point contacts lying in a region circumscribed by the input electrode and separated thereby from the base electrode.

Moreover, while semiconductive body **10** has been specifically designated hereinbefore as being constituted of N-type germanium, it is to be understood that this body may alternatively be constituted of other semiconductive materials, e.g. P-type germanium, P-type silicon, or any

of various intermetallic compounds such as indium antimonide. In each of these cases, the natures of the rectifying elements may be modified in manners well known to those skilled in the art, to provide the requisite properties as described hereinbefore.

Although we have described our invention with particular reference to specific embodiments thereof in order to provide a degree of definiteness such as to enable one skilled in the art to practice it, it is to be understood that the invention is in no way limited to such arrangements and methods, but is susceptible of embodiment in any of a wide variety of forms without departing from the scope thereof.

We claim:

1. A signal-translating device comprising: a body of semiconductive material having two substantially plane-parallel surfaces; a substantially circular minority-carrier injecting electrode applied to one of said surfaces; a substantially circular rectifying electrode for collecting said minority carriers, said collecting electrode being positioned on the other of said surfaces substantially coaxially with said injecting electrode; a first annular rectifying electrode positioned on said one surface substantially concentrically with said injecting electrode and a second annular rectifying electrode positioned on said other surface substantially concentrically with said collecting electrode and opposite to said first annular rectifying electrode, each of said first and second annular rectifying electrodes having an inner diameter which exceeds the outer diameter of said injecting electrode by an amount greater than twice the diffusion path-length of said minority-carriers in said body; third and fourth annular rectifying electrodes applied respectively to said one and said other surfaces of said body, said third and fourth annular electrodes having respective inner diameters exceeding the respective outer diameters of said first and second annular electrodes and being positioned concentrically therewith; and an ohmically contacting element applied to a portion of said body lying outside of the regions thereof circumscribed by said third and fourth annular rectifying electrodes.

2. A signal-translating device according to claim 1, wherein said body of semiconductive material is constituted of n-type germanium; wherein said collecting electrode has an outer diameter greater than said outer diameter of said injecting electrode; wherein said first and second annular rectifying electrodes have substantially the same outer and inner diameters, said last-named inner diameter exceeding by said amount said outer diameter of said collector electrode; wherein said third and fourth annular rectifying electrodes have substantially the same outer and inner diameters; and wherein each of said injecting, said collecting, and said first, second, third and fourth annular rectifying electrodes is a surface-barrier electrode.

3. A signal-translating device according to claim 1, said device comprising means for applying a forward-biasing potential to said injecting electrode; means for applying a first reverse-biasing potential to said collecting electrode; means for applying to said third and fourth annular rectifying electrodes a second reverse-biasing potential; means for applying to said first and second annular rectifying electrodes a third reverse-biasing potential having a value less than the value of each of said first and second potentials; means for supplying to one of said third and fourth annular rectifying electrodes a signal having intelligence variations; and means for deriving an output signal from said collecting electrode in response to said intelligence signal.

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